

# Very Low Insertion Loss Arrayed-Waveguide Grating with Vertically Tapered Waveguides

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**Abstract**—We propose and demonstrate a very low insertion loss silica-based arrayed-waveguide grating (AWG) achieved using a novel structure, which has vertically tapered waveguides between arrayed-waveguides to reduce the slab-to-arrayed-waveguide transition loss. A spot-size converter is also incorporated in the AWG to reduce the fiber-to-waveguide coupling loss. The structure can be formed by a process involving the conventional photolithography and reactive ion etching. The structure provided a loss reduction of 1.5 dB. Moreover, we have successfully obtained a minimum insertion loss of 0.75 dB with a crosstalk of -40 dB and polarization-independent operation.

**Index Terms**—Arrayed-waveguide grating (AWG), insertion loss, silica-based, spot-size converter, transition loss, vertically tapered waveguide.

## I. INTRODUCTION

ARRAYED-waveguide gratings (AWGs) play important roles in the rapidly growing dense wavelength division multiplexing (DWDM) systems as filters and multi/demultiplexers because of their low insertion loss, high stability, and good mass-producibility. For such passive devices, a lower insertion loss is advantageous and a low insertion loss is essential—especially for multiple AWG usage such as add/drop multiplexers and in metropolitan/access area networks where optical amplifiers cannot be employed [1]. The insertion loss of a silica-based AWG, for example, is around 3 dB, and has two main origins. One is the transition loss that occurs at the junction between slab and arrayed-waveguides. This is because there are gaps between arrayed-waveguides at the junction, and this leads to a field mismatch between the slab and arrayed-waveguides. The gap size is limited by the finite resolution of the fabrication process. Double etch [2] and e-beam lithography techniques [3] have been reported as ways of reducing the transition loss of InP-based AWGs, but they still have greater insertion losses than silica-based AWGs. For silica-based AWGs, on the other hand, there has been no fabrication report on transition loss reduction, only a design proposal [4]. The other insertion loss origin is fiber-to-waveguide coupling loss, caused by the field mismatch between a fiber and a waveguide, which varies with the combination of core size and refractive index of both fiber and waveguide. The fiber coupling loss for single-mode fiber can be reduced by introducing a lower index waveguide, e.g.,  $\Delta = 0.4\%$ , but that

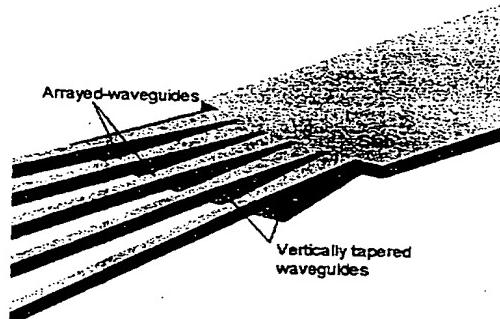


Fig. 1. Schematic structure of a novel AWG: Vertically tapered waveguides are inserted between arrayed-waveguides. Only six vertically tapered waveguides are shown for simplicity.

results in a larger bending radius and larger circuit size [4], [5]. Spot-size converters are another way to reduce the coupling loss, and several approaches have been reported [6], [7].

In this paper, we report our proposal and fabrication of a novel AWG that uses vertically tapered waveguides between arrayed-waveguides to reduce transition loss. The vertically tapered waveguides allow gaps between arrayed-waveguides and can be fabricated with a widely used photolithographic technique. We also attached spot-size converters to the input and output waveguides to reduce fiber coupling loss. We adopted a laterally tapered structure to control the converter shape through a photo-mask. We employed waveguides with a 0.75%  $\Delta$ , with which many kinds of AWGs have been developed, and obtained an AWG with a minimum insertion loss of 0.75 dB, including fiber coupling loss. We also obtained a background crosstalk of -40 dB and polarization-independent operation.

## II. STRUCTURE

The schematic structure of our novel AWG with vertically tapered waveguides is shown in Fig. 1. Near the junction, the vertically tapered waveguides are formed between the arrayed-waveguides with a "web-footed" structure. The height of the vertically tapered waveguides is almost the same as that of the other waveguides (in our case, 6  $\mu\text{m}$ ) at the junction and they gradually become lower with distance from the junction. The height reaches zero at a distance  $L$ . As this structure causes the field in the transition region to change gradually, the light from a slab can propagate smoothly into the arrayed-waveguides through the vertically tapered waveguides, and vice versa. We calculated the insertion loss of an AWG with the web-footed

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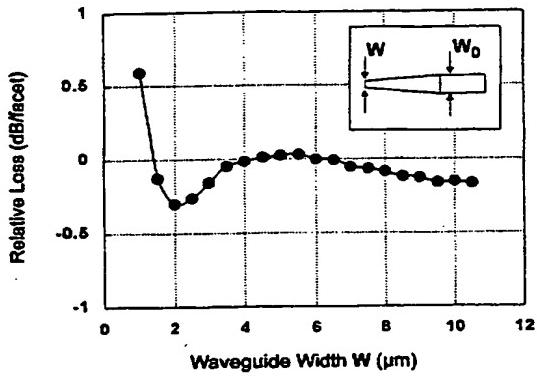


Fig. 2. Coupling loss characteristics between single-mode fiber and spot-size converter, where the taper length and  $W_0$  were 500  $\mu\text{m}$  and 6  $\mu\text{m}$ .

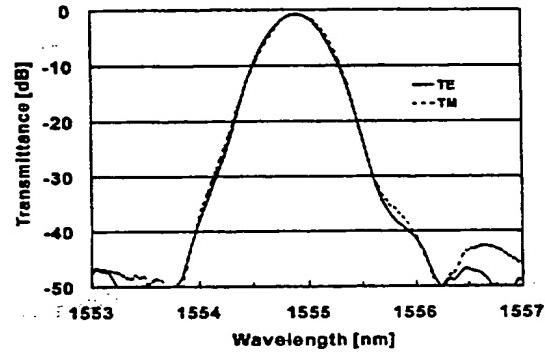


Fig. 3. Transmission spectra of novel AWG with web-footed structure and spot-size converters, and with  $\Delta$  of 0.75% (a) for TE and TM modes at central channel (b) for TE mode of 32 channels.

structure using the beam propagation method (BPM), and confirmed a loss reduction of 1.0 dB when  $\Delta$  and  $L$  were 0.75% and 400  $\mu\text{m}$ , respectively.

To reduce the fiber coupling loss, we adopted laterally tapered waveguides, which were formed at the same time as the web-footed structure but had no vertical taper, as spot size converters at the input and output waveguides. The coupling loss variation at 1550 nm is shown in Fig. 2 as a function of the waveguide width ( $W$ ) at the end taper, where the taper length and  $W_0$

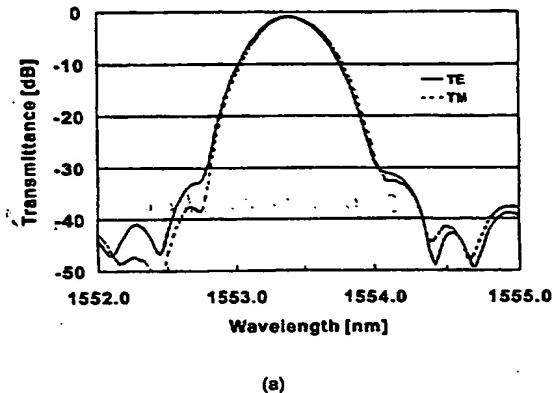


Fig. 4. Transmission spectra of novel AWG with web-footed structure, and with  $\Delta$  of 0.45% (a) for TE and TM modes at central channel (b) for TE mode of 32 channels.

were 500  $\mu\text{m}$  and 6  $\mu\text{m}$ , respectively. The coupling loss between a 6- $\mu\text{m}$ -wide (6- $\mu\text{m}$ -high) waveguide and a single-mode fiber was used as a basis. We found that a maximum coupling loss reduction of 0.3 dB per facet can be obtained with a 2- $\mu\text{m}$ -wide waveguide.

### III. EXPERIMENTAL RESULTS

We fabricated a 32-channel AWG with channel spacings of 100 GHz, a free spectral range of 5800 GHz, and a 0.75%  $\Delta$  to confirm the efficiency of the web-footed structure and spot size converter. The AWG, vertically tapered waveguides, and converters were formed simultaneously by a combination of the flame hydrolysis deposition, photolithography, and reactive ion etching of silica-based glass. The vertical taper was created by controlling the lithographic and etching conditions, while the converter was formed through a photo-mask under the same conditions. These conditions will be reported in detail in the near future. The fabricated vertical taper was 3.5  $\mu\text{m}$  wide at the junction and had a length  $L$  of 350  $\mu\text{m}$ . The converters had the taper length of 500  $\mu\text{m}$ , a width  $W$  of 2  $\mu\text{m}$ , and were 6  $\mu\text{m}$  high. To eliminate the polarization dependence of the AWG, we used dopant-rich silica-based glass in which the amount of dopant was modified to prevent the AWG characteristics from deteriorating [8], [9]. The polarization independence allows us

to remove the half-wave-plate [10], which in turn reduces insertion loss by 0.3 to 0.5 dB.

The transmission spectra for the TE and TM modes of the central channel of the fabricated AWG are shown in Fig. 3(a). We used a polarization maintained fiber as the input and a single-mode fiber as the output. Both fibers had the same spot size. The insertion loss was 0.75 dB and the polarization dependence was smaller than 0.03 nm. The removal of the converter increased the insertion loss by 0.5 dB, whereas the loss of the conventional AWG, which is not shown in the figure, was 2.75 dB. Thus, it is confirmed that the web-footed structure reduced the insertion loss by about 1.5 dB for an AWG with a  $\Delta$  of 0.75%. Fig. 3(b) shows the transmission spectra of 32 channels in the AWG shown in Fig. 3(a). The insertion loss ranges from 0.75 to 1.22 dB for the 32-channel ports, but for the central 16 channels all of the insertion losses are less than 0.9 dB (0.75 to 0.87 dB). The background crosstalk is about -40 dB. It is noted that the web-footed structure and the spot size converter caused no polarization dependence and had no detrimental effect on the AWG characteristics.

This web-footed structure has also been applied to an AWG with a  $\Delta$  of 0.45% and with no spot size converter. The fabricated vertical taper was  $3.5 \mu\text{m}$  wide and had a length  $L$  of  $350 \mu\text{m}$ . The transmission spectra for the central channel and 32 channels of the AWG are shown in Fig. 4. A low insertion loss of 0.8 dB was also obtained with a loss reduction of 0.5 dB. Therefore, the web-footed structure is effective for waveguides with various  $\Delta$  values.

#### IV. CONCLUSION

We proposed a novel AWG with vertically tapered waveguides between arrayed-waveguides (web-footed structure) and demonstrated an insertion loss of less than 1 dB. The web-footed structure reduced the insertion loss by 54.5% and we obtained a minimum insertion loss of 0.75 dB with the AWG using spot-size converters. We also obtained a crosstalk of about -40 dB with polarization-independent operation. Since this web-footed structure is useful for waveguides with various  $\Delta$  values and the effect is basically independent of AWG type, such as the

Gaussian type described here and the flat-response type [11], the novel AWG will be widely applicable in WDM devices.

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